

## CHAPTER 117

### Prediction of wind-driven transport rates

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#### ABSTRACT

The rate of wind-driven sand movement in a dune field is an important parameter needed to establish management strategies for sand dune fields. Until recently not much attention has been given in engineering circles to the possible effect of wind-blown sand transport. However, there is a wealth of literature on the subject which goes back as far as 1936. A study of literature reveals that there are at least 16 formulae for the prediction of the aeolian transport rates which are readily available. This paper describes a technique which utilizes these 16 formulae in the most effective manner for predicting the best estimate of the **potential** wind-blown transport rate. Restrictions on the applicability of the method are discussed and fields for further research are recommended.

#### 1. BACKGROUND

Sediment pathways and sediment budgets in the coastal zone often depend on the balance between wave- and current-driven sediment movement in the nearshore region and wind-driven transport of sand through driftsand areas connecting adjacent bays or embayments. The management of these areas often relies on knowledge of the relative magnitude of the transport in the underwater and driftsand areas.

Evaluation of the merit of stabilizing a driftsand area is a case in point. On the one hand the stabilization may be essential to prevent inundation of townships or valuable agricultural land by driftsands. On the other hand this same driftsand field may be a vital source of sand supply for the beaches downwind of the driftsands. A proper decision about the extent and method of stabilization can then only be made once a reliable estimate has been made of the amount of wind-driven sand movement that could potentially take place annually.

However, the prediction of the aeolian sand transport can only be as good as the wind data. This is frequently a problem. Data of sufficient quality and of long enough duration are needed. A recording period of at least one year and preferably longer is required. Usually such data are only available at focal points for development along the coast with the result that in the case of remote sites one frequently has to resort to the use of visual estimates of wind statistics gathered by lighthouse keepers or to measured data from sites which may be totally unsuitable for application to the site under consideration.

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Visual estimates of wind characteristics have been made regularly by Voluntary Observing Ships (VOS) since 1960. The estimates are incorporated in six-hourly weather observations of these ships and relayed to the major weather forecasting bureau. Because the deck officers who compile the weather observations are mostly experienced seamen the quality of their estimates is usually good. A vast number of the VOS wind observations for the period from 1960 are available and these cover the entire South African coastline. On the basis of a comparison between VOS wind data and anemometer recordings from shore-based stations Swart (1986) concluded that VOS wind data can be transformed into representative wind statistics on land in the coastal zone.

This paper summarizes the available techniques for the prediction of wind-driven transport, which are based on plane-bed transport situations, and investigates means of applying these techniques to the turbulent wind field situations encountered in driftsand areas.

## 2. AEOLIAN TRANSPORT PREDICTORS

### 2.1 General

The predictors for the magnitude of potential aeolian sand transport which have traditionally been used most extensively are those of Bagnold (1941), Kawamura (1951) and O'Brien (1936). More recently Hsu (1971a) and Mossa (1980), amongst others, developed modified predictors. Notwithstanding the large time span between the development of the various formulae, they are all very similar in appearance and in the wind transport rates which are predicted.

The reason for the similarity of appearance of the different formulae is that the mechanism which causes the wind-blown transport of sand is well understood. As soon as the shear stress exerted by the wind field on the sand surface exceeds a critical value, grains start to move. Although certain researchers neglect the critical shear stress in their formulation, all formulae equate the potential aeolian sand transport to some function of the shear stress.

The predicted wind transport rates are similar because the empirical coefficients in the different formulae were updated as more data became available.

This section contains a summary of the equations developed by the researchers mentioned above. To facilitate their easy application all these formulae were transformed into metric units and the transport rates expressed in cubic metres per metre per second, by assuming a porosity of 0.7 in the sand body before transport takes place. The limitations of the predictors will be given here to the extent it is given in the original publications. A more in-depth discussion of each of the 16 formulae can be found in Swart (1987a).

These formulae all relate to the situation where the wind is blowing over a **dry** sand surface, whereas this is obviously not always the case in nature. Therefore, the effect of moisture in the sand on the transport is discussed briefly in Section 2.3. More details can again be found in Swart (1987a).

The following symbols are used extensively in the equations:

- $S_a$  = potential aeolian sand transport rate, expressed in  $m^3/m/s$ ;  
 $u_{*w}$  = the shear velocity at the sand surface due to wind action, expressed in  $m/s$ , which is equal to  $(\tau_0/\rho_a)^{1/2}$ ;  
 $u_{*wc}$  = critical value of shear velocity above which movement takes place, in  $m/s$ ;  
 $\tau_0$  = total shear stress at the sand surface due to wind action;  
 $\rho_a$  = mass density of air in  $kg/m^3$  ( $1.29 kg/m^3$ );  
 $\rho_s$  = mass density of sand in  $kg/m^3$  ( $2650 kg/m^3$ );  
 $g$  = gravitational acceleration in  $m/s^2$  ( $9.8 m/s^2$ );  
 $D_{50}$  = median grain diameter of sand, in  $m$ .

The shear velocity  $u_{*w}$  can be determined from the wind velocity profile above the sand surface. The way in which this is done for cases in which the velocity profile is not specifically measured, such as would be the case when predictions are being done, is open to discussion. This aspect will be dealt with in Section 3.

In most of the original publications the potential aeolian sand transport rate is denoted by  $q$  and is expressed in  $g/cm/s$ . The shear velocities  $u_{*w}$  and  $u_{*wc}$ , where subscript  $w$  incidentally refers to wind, are called  $u_*$  and  $u_{*c}$  in the original publications and are given in  $cm/s$ . The mass densities are given in  $g/cc$  in the original papers and the gravitational acceleration is expressed in  $cm/s^2$ . All these cgs units have been transformed into metric units for this paper, as indicated above. Symbols used only occasionally will be defined in the text.

## 2.2 Predictive Formulae

**Bagnold** (1941) found a formulation for the potential aeolian transport on the assumption that grains move downwind with a bouncing motion near the sand surface. By using data presented by Bagnold (1954), Iwagaki (1958) and Kubota et al. (1982) regarding the empirical constant, the following formula (in metric units) is found:

$$S_a = 0.052 D_{50}^{0.5} \left(\frac{\rho_a}{g}\right) u_{*w}^3 \quad (\text{in } m^3/m/s) \quad \dots(1)$$

It appears that the data on which the coefficient in equation (1) is based can be summarized as follows:

$$\begin{aligned} \text{Range of } D_{50} &: 0.20 \times 10^{-3} \text{ m to } 0.40 \times 10^{-3} \text{ m} \\ \text{Range of } u &: 0.14 \text{ m/s to } 2.85 \text{ m/s.} \end{aligned}$$

**Kawamura** (1951) assumed that the shear stress at the sand surface is composed of two components, namely, that caused by the wind and that caused by the impact of saltating and moving sand particles. By using the incipient motion criterion of Bagnold (1941) and experimental data of Kawamura (1951), Horikawa and Shen (1965) and Kubota et al. (1982) the original Kawamura formula can be written as:

$$S_a = 8.24 \times 10^{-4} \left(\frac{\rho_a}{g}\right) (u_{*c} - u_{*wc}) (u_{*w} + u_{*wc})^2 \quad \dots(2a)$$

(in  $m^3/m/s$ )

where

$$u_{*wc} = 0.1 \left[ \left( \frac{\rho_s - \rho_a}{\rho_a} \right) g D_{50} \right]^{1/2} \quad \dots(2b)$$

The range of conditions for which this formula is valid is the same as that for the Bagnold formula, namely:

$$\begin{aligned} \text{Range of } D_{50} &: 0.20 \times 10^{-3} \text{ m to } 0.40 \times 10^{-3} \text{ m} \\ \text{Range of } u_{*w} &: 0.14 \text{ m/s to } 2.85 \text{ m/s.} \end{aligned}$$

**O'Brien and Rindlaub** (1936) developed an empirical formula on the basis of field experiments which was transformed by Horikawa (1981) and the present author to

$$S_a = 5.473 \times 10^{-5} (u_{*w} + 0.108)^3 \quad \dots(3)$$

for  $u_{*w} > 0.20 \text{ m}$ .

The range of conditions for which this formula is valid, is as follows:

$$\begin{aligned} \text{Range of } D_{50} &: D_{50} = 0.20 \times 10^{-3} \text{ m} \\ \text{Range of } u_{*w} &: \sim 0.20 \text{ m/s to } 0.60 \text{ m/s.} \end{aligned}$$

**Hsu** (1971a, 1971b, 1972, 1973, 1974a, 1974b) developed on the basis of field measurements a relationship between a shear Froude number and the potential aeolian sediment transport. Empirical coefficients were determined by using laboratory and field data of Bagnold (1941), O'Brien and Rindlaub (1936), Zingg (1952), Kawamura (1951), Horikawa (1960), Belly (1962) and Kadib (1964, 1965).

It can be written in metric units as:

$$S_a = 3.434 \times 10^{-9} \exp(4.970 D_{50}) \left[ \frac{u_{*w}}{(g D_{50})^{1/2}} \right]^3 \quad \dots(4)$$

(in  $m^3/m/s$ ).

The range of conditions for which this formula is valid, is as follows:

$$\begin{aligned} \text{Range of } D_{50} &: 0.15 \times 10^{-3} \text{ m} \leq D_{50} \leq 1.0 \times 10^{-3} \text{ m} \\ \text{Range of } u_{*w} &: 0.18 \text{ m/s} \leq u_{*w} \leq 2.85 \text{ m/s.} \end{aligned}$$

Hsu (1974a) only shows a range of  $u_{*w}$  extending to 1.0 m/s, but the tests with high wind shear velocities, performed by Kubota *et al.* (1982), provided another data point which is in agreement with equation

(4), which in effect extends the range of  $u_{*w}$  to the value shown above.

**Mossa** (1980), working under the guidance of Hsu, reanalysed the data which led to equation (4) and found a slightly modified formulation, which is given below although it does not really add any new information over and above that already reported:

$$S_a = 3.475 \times 10^{-9} \exp(4.910 D_{50}) \left[ \frac{u_{*w}}{(g D_{50})^{1/2}} \right]^3 \quad \dots(5)$$

(in  $m^3/m/s$ ).

The range of variables is the same as that for the original Hsu formula.

**Chiu** (1970) used measurements of wind-driven transport rates at different levels above the sand surface, which he integrated over depth, to obtain an expression for the total wind-driven transport rate. He then used data by Bagnold (1941), Zingg (1952), Horikawa (1960), Belly (1962) and Kadib (1964) to generalize his results to include a range of grain sizes and values of the sorting coefficient  $s$  (where  $s^2 = D_{75}/D_{25}$ ). In metric form his results finally lead to:

$$S_a = 5.5 \times 10^{-4} f(s, D_{50}) (2.13 + 0.39 u_{*w}) \left( \frac{\rho_a}{g} \right) u_{*w}^3 \quad \dots(6a)$$

$f(s, D_{50})$  is for one formulation of Chiu taken as unity and in the other as

$$f(s, D_{50}) = \exp(-1.78 \times 10^{-3} (s^2 - 1)^{1/2}) i \left[ \frac{s^3}{D_{50}} (1.6641 - s^2)^2 \right]^{1.1} \quad \dots(6b)$$

with  $i = 1$  for  $s < 1.29$  and  $i = -1$  for  $s \geq 1.29$ .

The range of values of the variables to which these expressions apply is:

$$\begin{aligned} \text{Range of } D_{50} &: 0.145 \times 10^{-3} \text{ m} \leq D_{50} \leq 1.0 \times 10^{-3} \text{ m} \\ \text{Range of } u_{*w} &: 0.24 \text{ m/s} \leq u_{*w} \leq 1.35 \text{ m/s} \\ \text{Range of } s &: 1.01 \leq s \leq 1.41. \end{aligned}$$

**Kadib** (1964, 1965, 1966) investigated the concepts developed by Einstein (1950, 1953) for the description of sediment motions by flowing rates, and concluded that turbulence, "particle hiding" and flow variation are also important parameters in aeolian transport, as well as in addition also the effect of saltating sand grains on the threshold of particle motion. Kadib assumed that the relationship between the dimensional sediment load intensity  $\Phi$  and a dimensionless parameter  $\psi_*$  which related the submerged particle weight and the lift force on the particle, derived by Einstein for water flow, is also valid for air flow. In addition, he expressed both the particle hiding and the effects of particle impact on the force balance as a correction to the

lift force. He used his own data as well as that of O'Brien and Rindlaub (1936), Zingg (1952), Horikawa (1960) and Belly (1962) to determine this correction factor. His results are given graphically in Kadib (1965). In order to make the method more widely applicable, Swart (1987b) evaluated the high shear data of Kubota et al. (1982) in the same manner described above and performed curve-fitting to the combined graphical results. The final result was obtained:

$$S_a = 8.25 \times 10^{-4} \rho_s \Phi \left( \frac{\rho_s - \rho_a}{\rho_a} \right)^{1/2} (gD_{50}^3)^{1/2} \quad \dots(7a)$$

(in  $m^3/m/s$ ).

where

$$\Phi = \begin{cases} 0 & \text{for } \psi_* \geq 25 \\ 29[\psi_*^{-2.66} - 1.912 \times 10^{-4}] & \text{for } 10 < \psi_* < 25 \\ 6.497 \psi_*^{-2.05} & \text{for } \psi_* < 10 \end{cases} \quad \dots(7b)$$

$$\psi = \left( \frac{\rho_s - \rho_a}{\rho_a} \right) \left( \frac{gD_{50}^3}{u_{*w}^2} \right) \quad \dots(7c)$$

$$\psi_* = \frac{\xi}{I} \psi \quad \dots(7d)$$

$$\frac{\xi}{I} = \begin{cases} 2.5 - 0.125\psi & \text{for } \psi \leq 10 \\ 6.265 \psi^{-0.7} & \text{for } \psi > 10 \end{cases} \quad \dots(7e)$$

More details of the above formulations can be found in Swart (1987a, 1987b).

On the basis of the data included in Kadib (1965) and those on high shear velocities added in this study, the range of application of the Kadib method is as follows:

$$\begin{aligned} \text{Range of } D_{50} &: 0.145 \times 10^{-3} \text{ m} \leq D_{50} \leq 1.0 \times 10^{-3} \text{ m} \\ \text{Range of } u_{*w} &: 0.24 \text{ m/s} \leq u_{*w} \leq 2.89 \text{ m/s.} \end{aligned}$$

**Nakashima** (1979) studied, with reference to the control of blown sand under field conditions, wind-driven sand transport, with specific reference to the threshold shear velocity and its dependence on grain size, particle shape parameter and the water content of the sand surface. Some very interesting aspects of Nakashima's work are referred to in Sections 2.3 and 2.4 and are discussed in more detail in Swart (1987a). The potential transport over a dry sand surface, as given Nakashima and expressed in metric units, is given by:

$$S_a = 1.79 \times 10^{-3} D_{50} u_{*w} \rho_s \left[ \left( \frac{u_{*w}^2 \rho_a}{gD_{50} \rho_s} \right)^{0.8} - 0.03 \right] \quad \dots(8)$$

On the basis of the data contained in Nakashima (1979), the range of application of equation (8), is as follows:

Range of  $D_{50}$  :  $0.22 \times 10^{-3} \text{ m} \leq D_{50} \leq 1.61 \times 10^{-3} \text{ m}$

Range of  $u_{*W}$  :  $0.2 \text{ m/s} \leq u_{*W} \leq 1.6 \text{ m/s}$

Range of  $s_1 = (D_{84}/D_{16})^{1/2}$  :  $1.246 \leq s_1 \leq 1.802$ .

**Tsuchiya and Kawata** (1972, 1975) performed a rigorous, theoretical treatment of all aspects related to saltation of sand grains. In the 1972 paper the various elements of the theory were compared to data, and good agreement was found. In the 1975 paper three different theories were derived on the basis of the various saltation processes described in the original paper, which can in metric units be written as:

$$(1) S_a = 0.5 u_{*W} D_{50} (\lambda)^{1/2} a_T a_1 F_1 (\tau_* - \tau_{*C}) \quad \dots(9a)$$

$$(2) S_a = u_{*W} D_{50} F_2 (\tau_* - \tau_{*C}) \quad \dots(9b)$$

$$(3) S_a = u_{*W} D_{50} F_3 (\tau_* - \tau_{*C}) \quad \dots(9c)$$

In the above  $F_1$ ,  $F_2$  and  $F_3$  and  $\lambda$ ,  $a_T$  and  $a_1$  are parameters defined in the original publication by **Tsuchiya and Kawata** (1975). Furthermore,  $\tau_*$  is the bed shear defined as:

$$\tau_* = \frac{u_{*W}^2}{(\rho_s/\rho_a - 1) g D_{50}} \quad \dots(9d)$$

and  $\tau_{*C}$  is the critical shear stress assumed equal to 0.01, which corresponds exactly with equation (2b).

The expressions (9a) to (9c) were derived from first principles in the 1975 paper and as such place no restrictions on the range of applicability, although saltation must of course take place for the theory to be valid. However, the various elements of the theory have been compared in the two papers referred to above with data covering the following range of variables:

Range of  $D_{50}$  :  $0.144 \times 10^{-3} \text{ m} \leq D_{50} \leq 0.715 \times 10^{-3} \text{ m}$

Range of  $u_{*W}$  :  $0.054 \text{ m/s} \leq u_{*W} \leq 1.22 \text{ m/s}$ .

**Zingg** (1952) did wind tunnel experiments to investigate the relationships between wind speed and shear velocity at the sand surface on the one hand and between shear velocity and sediment transport. He obtained a modification of the original formula by **Bagnold** (1941);

$$S_a = 0.023 D_{50}^{0.75} (\rho_a/g) u_{*W}^3 \quad \dots(10)$$

The range of variables on which this expression is based, is as follows:

Range of  $D_{50}$  :  $0.20 \times 10^{-3} \text{ m} \leq D_{50} \leq 0.715 \times 10^{-3} \text{ m}$

Range of  $u_{*W}$  :  $0.3 \text{ m/s} \leq u_{*W} \leq 1.82 \text{ m/s}$ .

**Zanke** (1978) separated bed-load  $q_b$  and suspended load and  $q_s$  from each other and demonstrated that an earlier theory for the prediction of sediment transport under uniform current flow (**Zanke**, 1978) is

valid for air flow as well. In the latter case he calibrated the theoretical expressions against field data gathered on the German North Sea coast, and then checked the resulting formulae against data of Exner (1928), O'Brien and Rindlaub (1936) and Kadib (1965).

Zanke (1980) proposes that the total transport is given by one of the following two versions:

$$S_a = \begin{cases} Q_b + Q_s \\ Q_b \end{cases} \quad \dots(11a)$$

where the expressions for bed load and suspended load are as follows:

$$Q_b = 1.5 \times 10^{-6} \left( \frac{v_1^2 - v_c^2}{w} \right)^2 D_*^4 v \frac{1}{\rho} \quad \dots(11b)$$

$$\text{and } Q_s = 1.5 \times 10^{-6} \left( \frac{(v_1^2 - v_c^2)(v_1^2 - v_{10}^2)}{w^4} \right) D_*^4 v \frac{1}{\rho} \quad \dots(11c)$$

where  $\nu$  is the kinematic viscosity of air,  $\rho$  is the porosity, taken to be equal to 0.7 by Zanke, and  $v_1$  is the wind velocity at 1 cm above the sand surface, obtained from measurements of wind speed 10 m above the surface by assuming a logarithmic velocity profile.

$D_*$  is a dimensionless grain diameter;

$$D_* = \left\{ \frac{(\rho_s/\rho_s - 1)g}{\nu^2} \right\}^{1/3} D_{50} \quad \dots(11d)$$

The range of variables used to establish equations (11) is:

$$\text{Range of } D_{50} : D_{50} = 0.24 \times 10^{-3} \text{ m.}$$

The theory was, however, tested against data collected by O'Brien (1936), Kadib (1965) and Exner (1928). This extends the range to:

$$0.145 \times 10^{-3} \text{ m} < D_{50} < 1.0 \times 10^{-3} \text{ m}$$

Range of  $v_{10m}$  (velocity at 10 m)  $v_{10} < 20$  m/s.

The range of  $u_{*w}$  in the measurements of O'Brien, Kadib and Exner referred to above is 0.2 m/s to 2.89 m/s.

**Horikawa et al.** (1983), in a useful summary of available formulae for the prediction of wind-blown sand transport, concluded that most formulae failed to predict accurately transport rates in the case of sands with a wide grain size distribution, characterized by a sorting coefficient  $u_c (= D_{60}/D_{10}) \gg 1$ . Swart (1987b) used the first tentative results of Horikawa et al. (1983) to reanalyse the original data used to establish all the formulae given herein and obtained the following:

$$S_a = K_{MBKS} \left(\frac{\rho_a}{g}\right) (u_{*W} - u_{*WC}) (u_{*W} + u_{*WC})^2 \quad \dots(12a)$$

This Modified-Bagnold-Kawamura-Swart formula is identical to the Kawamura formula (equation (2)) except for the coefficient, which is given by:

$$K_{MBKS} = 5.49 \times 10^{-4} u_{ca}^4 \left(\frac{D_{50a}}{D_{50r}}\right)^{-0.5} \left(0.02 \left(\frac{D_{50}}{D_{50r}}\right) + 0.08\right) (u_c - 1)^{-2/3} \quad \dots(12b)$$

where  $D_{50r}$  = reference grain size =  $0.2 \times 10^{-3}$  m

$$D_{50a} = \beta u_* + 2.4 \times 10^{-3} \quad \dots(12c)$$

If  $D_{50a} > D_{50}$  then  $D_{50a} = D_{50}$

$$\beta = 1.5 \times 10^{-4} (1 - \sigma_u) \quad \dots(12d)$$

$$\sigma_u = \frac{D_{60}}{D_{90}}$$

$$u_{ca} = \alpha u_* + 1.5 \quad \dots(12e)$$

If  $u_{ca} > u_c$  then  $u_{ca} = u_c$

$$\alpha = 1 - \sigma_u$$

The range of variables on which this formulation is based, is as follows:

$$\begin{aligned} \text{Range of } D_{50} &: 0.145 \times 10^{-3} \text{ m} \leq D_{50} \leq 1.0 \times 10^{-3} \text{ m} \\ \text{Range of } u_{*W} &: 0.054 \text{ m/s} \leq u_{*W} \leq 2.89 \text{ m/s} \\ \text{Range of } D_{60}/D_{10} &: 1.02 \leq D_{60}/D_{10} \leq 1.988 \\ \text{Range of } D_{60}/D_{90} &: 0.662 \leq D_{60}/D_{90} \leq 0.988 \end{aligned}$$

### 2.3 Transportation of moist sand

It is not the purpose of this paper to review the transportation of moist sand by wind action. However, because the sand is frequently moist when wind speeds capable of moving dry sand occurs, it is necessary to study this phenomenon. Horikawa, Hotta and Kubota (1982b) presented an excellent review of work done to date on blown sand on wetted sand surfaces. From this review it is clear that:

- (1) The problem of blown sand on wetted sand surfaces has not been conclusively studied yet and a number of problem areas still remain to be solved.
- (2) Wind-driven sand transport depends, amongst other things, on the water content of the sand layer, humidity, air temperature and solar radiation. It will be very difficult ever to use these

parameters on a routine basis for the prediction of wind-driven transport rates because of the scarcity (non-existence) of parallel statistics on the various variables. It is nonetheless important to quantify the effect on the transport rate of these variables.

- (3) In trying to predict the mechanism of blown sand on wet sand surfaces it will be necessary to know to what depth the sand is wetted by a rainfall of known intensity and duration as well as the manner in which the sand bed will dry out again. The rôle of sand characteristics, humidity, wind speed, air temperature and solar radiation needs to be addressed in this respect.
- (4) It would appear that the main differences between blown sand on wet and dry sand surfaces is that the critical wind speed when sand movement starts is increased on a wetted sand surface and that the variation of sediment concentration is different. It would, however, appear that as a first estimate the Kawamura type formula could be used for blown wet sand, provided that a modified incipient motion criterion is used. The results given by Horikawa *et al.* (1982a,b), Hotta *et al.* (1984) and Nakashima (1979) in this regard indicate that there is a wide divergency in the available data, perhaps because of the difficulty of accurately defining and measuring the moisture content in the sand bed.
- (5) More controlled measurements under laboratory conditions as well as field experiments are required to address the points raised above.

## 2.5 Discussion

This chapter has reviewed the available formulations for the prediction of blown sand on dry and wet surfaces. At present the best that can be done is to predict the transport of blown sand on a dry surface which, for ease of reference, is termed the **potential** sand transport. Apart from the problem of wet sand surfaces which was addressed in Section 2.3, there are a few other aspects which are particularly relevant to field application of the techniques, which will require systematic study. The two most important of these are:

- (1) The effect of the topography of the sand surface over which the wind blows on the shear velocity and the magnitude of the blown sand volume. To date little work has been done in this respect, but reference can be made to Nakashima (1979), Svasek and Terwindt (1974) and Harmse (1985).
- (2) The effect of vegetation cover has not been addressed quantitatively. Particularly in the case of blown-sand control or dune management this aspect, coupled with the previous point on topography, is of major importance. In this respect reference can be made to Fryberger *et al.* (1984), Illenberger (1986) and Swart and Reyneke (1987).

### 3. DETERMINATION OF SHEAR VELOCITY

Most of the formulae given in the previous chapter relate sand transport to the shear velocity at the bed. Mostly the shear velocity has to be computed on the basis of wind speed measurements at some distance above the sand surface. It is assumed that a logarithmic velocity profile exists, although this aspect still has to be addressed in the case of sand transport through dune fields where the dune height may be higher than 50 m. A number of different formulations, all of an empirical nature, exist in the body of literature referred to in Chapter 2. For the purpose of uniformity all the data used to determine these different relationships were plotted together in the form of a graph relating shear velocity with the wind speed at 2 m above the sand surface. This graph is shown here as Figure 1.

The best fit through the data points is given by

$$u_{*w} = 0.0275 u_2^{1.25} \quad \dots(13)$$

where  $u_2$  is the wind speed at 2 m above the sand surface.

The scatter in the data is encompassed by an upper and a lower envelope at a distance of plus or minus 20 per cent from the line defined by equation (13). This expression is used together with the logarithmic velocity law for all work reported on in this paper.

### 4. COMPARISON BETWEEN VOS WIND DATA AND SHORE-BASED ANEMOMETER RECORDS

In the determination of a sand budget as part of some preliminary engineering design it is often necessary to establish the contribution of the wind-driven component of sand transport to the overall budget. Under such circumstances the situation frequently arises that reliable wind statistics are not available in the close proximity of the area under consideration. It has been found quite useful then to rely, as a first approximation, on anemometer data recorded by Voluntary Observing Ships (VOS) in the coastal waters off the study site.

Swart (1987c) has shown that a reasonable similarity exists between the wind direction variation offshore and at the coast (see Figure 2). Obviously major topographic features modify the offshore wind climate but as a first estimate this is a reasonable assumption. In addition, he showed that the VOS wind speed is generally higher than that recorded at land-based anemometer stations. However, a comparison of all available shore-based anemometer wind speed data with corresponding VOS data showed that a good first estimate of wind speed can be obtained by

$$v_2 = 0.6 v_{VOS} \quad \dots(14)$$

(see Figure 3).

The purpose of the foregoing is not to suggest that there is no need for shore-based anemometer data, but only to provide first estima-

tes in the case of feasibility studies. In the final instance the variability of the wind field along the coast in sympathy with topographical variations is such that the only reliable results on aeolian transport will be those based on long-term wind data gathered on site.

## 5. SUMMARY OF PROCEDURES

The problem to be addressed is that 16 different formulae for the prediction of wind-driven sand transport on a dry sand surface were given in Chapter 2. Each of these have a different field of applicability. It has not been possible to demonstrate conclusively that any one of these formulations is clearly superior or inferior to the rest. The method described below gives a technique which allows the establishing of a good best estimate of the wind-blown transport rate.

For any given value of wind speed the wind speed is converted via the logarithmic law to a representative height above the ground of 2 m. The potential sediment transport rate is predicted for each of the 16 formulae and the answers ordered from the highest to the lowest. The highest 3 values and the lowest 3 are then rejected and the average of the central 10 estimates is then used as the predicted potential wind-blown transport rate according to the technique. Figure 4 gives an idea of the scatter involved for the case of  $D_{50} = 300 \mu\text{m}$  and  $v = 15 \text{ m/s}$ .

For normal application wind statistics from an anemometer of given height above the ground would serve as input data along with grain size details. It has been shown that data obtained from Voluntary Observing Ships can be used to obtain a good first estimate of the coastal wind climate. The results obtained from the analysis are represented in a creep diagram which is really an inverted rose.

Figure 5 gives an example of the aeolian creep diagram. It is possible to quantify the aeolian sand budget either on the basis of such a diagram or by using a tabular representation of the results.

## 6. FIELD VERIFICATION OF TECHNIQUE

The formulae given in Section 2, with the exception of those by Tsuchiya and Kawata (1975), were derived empirically. The empirical coefficients in the various formulations are therefore based on laboratory results or individual field experiments. This does not, however, give any indication of how any of these techniques will behave when applied to long-term wind statistics. For this purpose the method of application outlined in Chapter 5 was tested against long-term wind-data in situations where the sand drift was also known.

The method has been applied to a number of sites around the South African coast, amongst others the dune fields around Port Elizabeth and the dune fields on the South West African coast in the vicinity of Walvis Bay (see Figure 7). Measurements of dune advance rates at both these sites have been used to verify the technique. **Port Elizabeth** data indicate gross eastbound transport rates of  $68 \text{ m}^3/\text{m}/\text{yr}$  at Cape Recife (McLachlan, pers. com.), whereas Prestedge (pers. com.) estimates the net eastward movement in the area at  $45 \text{ m}^3/\text{m}/\text{yr}$  for the

period 1972 to 1981. East of the Sondags mouth McLachlan estimates, on the basis of dune advancement, a net eastbound transport rate of 35 to 42  $\text{m}^3/\text{m}/\text{yr}$  and a shoreward movement of about 30  $\text{m}^3/\text{m}/\text{yr}$ . The latter figure was revised by Illenberger (1986) to 22 to 30  $\text{m}^3/\text{m}/\text{yr}$ . Predictions with the technique described herein show the following potential rates:

Northbound:	gross	27 $\text{m}^3/\text{m}/\text{yr}$
	net	18 $\text{m}^3/\text{m}/\text{yr}$
Eastbound :	gross	78 $\text{m}^3/\text{m}/\text{yr}$
	net	45 $\text{m}^3/\text{m}/\text{yr}$

Calculations by Swart (1986) show variations in the predicted annual drift rate of a factor 3 on a year-to-year basis over an eleven-year period due to the variability of the wind field (Figure 6).

**Walvis Bay** data by Le Roux show northward volumetric dune advance rates of 120  $\text{m}^3/\text{m}/\text{yr}$  in the lower Kuiseb valley. Calculations with two different sources of wind data show northward aeolian transport rates of 109 and 122  $\text{m}^3/\text{m}/\text{yr}$  respectively. The good correspondence is shown in Figure 8.

## 7. CONCLUSIONS

This paper reviews the quantitative techniques for the prediction of windblown sand transport. The main conclusions reached are the following:

- (1) Sixteen different techniques were identified which can be used to predict potential wind transport rates over dry, unvegetated sand surfaces.
- (2) None of these is clearly superior or inferior to the others. Therefore a computational scheme was developed which utilizes the central ten predictions out of an ordered (high to low) set of 16 predictions for a given set of boundary conditions.
- (3) By application to two prototype examples where long-term data are available, it was shown that the method can be used to give accurate predictions of aeolian transport rates, provided that reliable wind statistics are available.
- (4) It was shown that Voluntary Observing Ships' wind data provide a good, first estimate of the uncontaminated wind field on the coast, provided that there are no major topographical features such as mountains to deflect the wind patterns locally.
- (5) The method described in this paper supplies potential windblown transport rates and neglects the effect on the transport of air temperature, the humidity, the moisture content of the soil, which is related to the amount and intensity of the rainfall, the salt content of the sand, the percentage of vegetation cover of the sand and the topography of the ground over which the wind is blowing.

## 8. RECOMMENDATIONS

It should be clear from the above that although the technique described supplies a reliable estimate of the **potential** windblown transport rate, there are still a number of factors which need to be researched further in detail before it will allow the prediction of prototype transport rates under variable prototype conditions. Much of this research is already underway. Factors which demand particularly urgent attention are those listed under item (5) in Chapter 7. Every effort should be made to co-ordinate the activities in this respect of the various researchers actively working toward understanding the effect of these parameters on the windblown transport rate.

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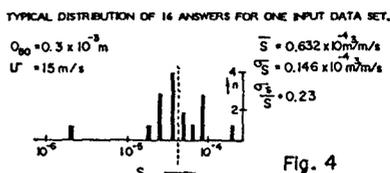
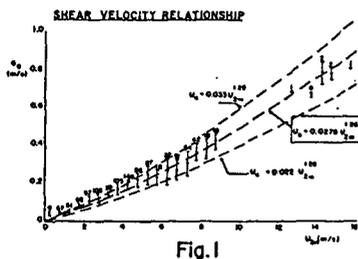


Fig. 4

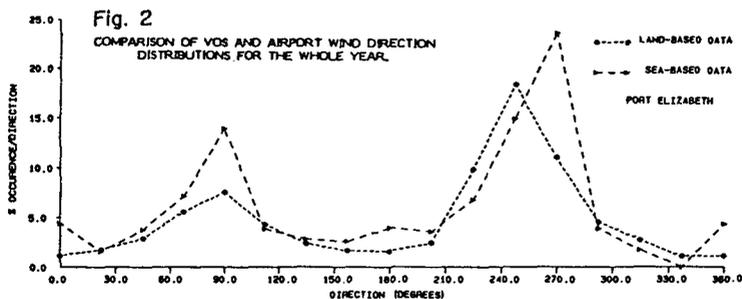


Fig. 2

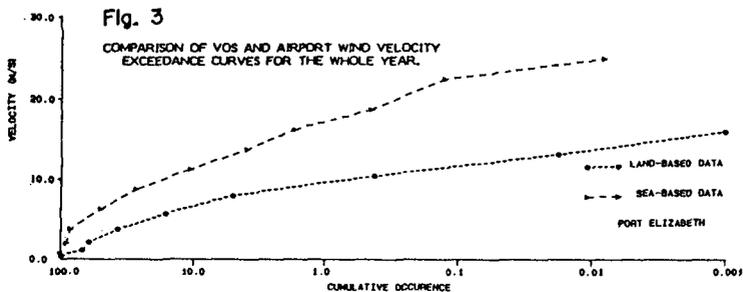


Fig. 3

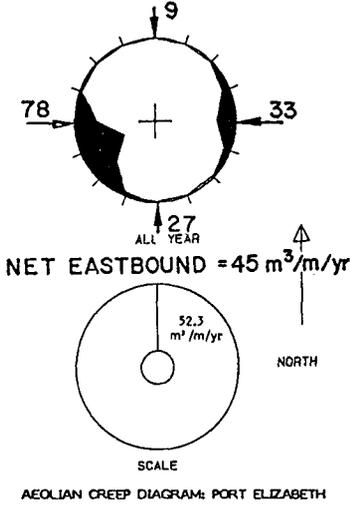


Fig. 5

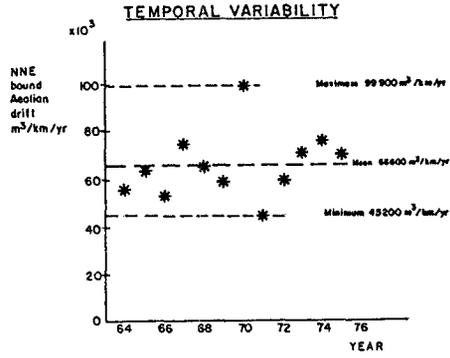


Fig. 6

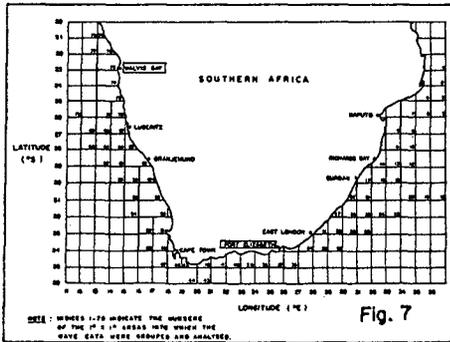


Fig. 7

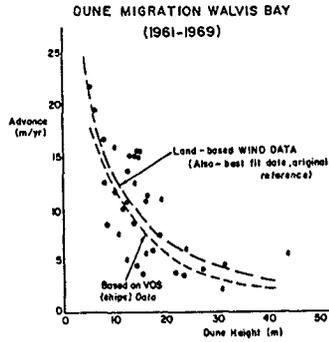


Fig. 8